Navy Special Warfare Enhanced Thermal Protection

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Award #: N0001498WX30131

LONG-TERM GOALS

This task seeks to provide an alternative to the commercially available divers' dry suit undergarment manufactured with standard thermal insulation. A novel thermal energy storage medium will be used to replace and/or supplement the standard thermal protection material and to enhance diver comfort level, improve physiological response to cold water operations, and support extended mission periods.

OBJECTIVES

The objectives of this task are to investigate the use of microencapsulated phase change material (MicroPCM®) technology to enhance the thermal protection of Navy Special Warfare (NSW) divers and to determine the levels of thermal protection achievable, i.e., how much and how long.

APPROACH

Commercial-off-the-shelf (COTS) dry diving suit ensembles include an outer, water-impermeable, rubberized garment and an inner thermal protection garment constructed with standard insulation media (e.g., DuPont Thermolite®, 3M Thinsulate®). The level of thermal protection of the undergarment is directly proportional to the thickness and density of the insulation media. For example, M400 Thinsulate® at 0.38 inches thick and 400 grams per square meter will give a moderate level of protection to the swimming diver; M600 Thinsulate® at 0.58 inches thick and 600 grams per square meter offers improved thermal protection. However, how does this translate to the thermal protection of a diver in a cold water diving scenario? Unmanned and manned, instrumented tests have shown that temperatures on the surface of the diver's skin approach that of the surrounding water in 2.5-3.0 minutes after entering cold water. This rapid skin temperature decrease from approximately 93° F normal skin surface temperature brings on thermophysiological shock to the body. The blood supply/ flow to the skin's surface is decreased as the body struggles to preserve its thermal balance; the metabolic rate is increased as a response to the onset of decreasing core temperatures, etc. Overall, the level of thermal protection in COTS diving suit ensembles is quite low and relatively insufficient to support extended duration diving missions of the NSW forces.

MicroPCM®s, a novel thermal energy storage technology, evolved from research and development by NSWCDD for use in extreme temperature protective clothing and by the National Aeronautics and Space Administration (NASA) and the U.S. Air Force (USAF) for use in space-based and high-altitude protective clothing. The MicroPCM® technology has demonstrated the potential for significantly

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
1998		**00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Navy Special Warfare Enhanced Thermal Protection	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center Dahlgren Division (NSWCDD),Code B53,17320 Dahlgren Rd,Dahlgren,VA,22448-5100**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002252.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**6**	

enhanced thermal protection of the NSW diver. Whereas, the properties of the standard insulation media function to preserve body heat while resisting transfer of the surrounding cold water temperatures, the time dependence is very short-lived. However, excess thermal energy ("body heat") transferred from the body's surface during diving ensemble donning and stored in the MicroPCM®s actually "block" the cold temperature transfer process for significant periods. In addition, as "body heat" is transferred to the MicroPCM®s, melting of the solid phase change medium occurs, providing a cooling sensation to the skin.

At the onset of the NSW Enhanced Thermal Protection task in FY96, eight steps were outlined to carry out the technological objectives. They are:

- Establish a development Team composed of a project leader with technical support from the diver R&D community and operational support from the diver/SEAL forces.
- Define the technical and operational requirements for the MicroPCM®-enhanced undergarment with regard to the commercial Thinsulate® undergarment.
- Determine the most suitable MicroPCM® for use in the diving scenario.
- Determine the carrier medium for the MicroPCM®, from none (i.e., pure MicroPCM® spheres) to high-weight percent MicroPCM®-loaded foams.
- Development of the undergarment configuration.
- Fabrication of the first generation (GEN I) prototypes.
- Technical (unmanned) testing of the GEN I prototypes on a Thermal Manikin.
- Diver (manned) testing of the GEN I prototypes.

To fulfil these technical objectives, NSWCDD decided to enlist into a research & development (R&D) Team scientific and technical expertise from the most significant manpower resources in the clothing & textile and diver regime. Team members are from the Navy Clothing & Textile Research Facility (NCTRF), Natick, MA; the Navy Experimental Diving Unit (NEDU), Panama City, FL; the Coastal System Station (CSS), Panama City, FL; the U.S. Naval Academy, Annapolis, MD; and Frisby Technologies, Clemmons, NC, the developer of the MicroPCM® technology.

WORK COMPLETED

The GEN I dry suit undergarments developed and fabricated from a combination Thinsulate®/ MicroPCM® foam insulation/thermal storage medium were evaluated in 4Q FY96 for thermodynamic performance on the thermal manikin at NCTRF. Results indicated a heat flux (i.e., heat loss) reduction in the torso of nearly 42%, whereas, the heat flux reduction in the forearm and lower leg approached 52%. The data were extracted from the performance tests and compared to identical tests with commercial M400 Thinsulate® dry suit undergarments.

The GEN I undergarments were similarly compared in diver performance tests in the NEDU test pool during 4Q FY96. Results were similar, but not as pronounced as in the thermal manikin tests. Divers reported that they felt cooler during dress-out of the dry suit ensemble and that they felt much warmer for a longer period of time in the 34° F water (with no thermal shock effects). However, an after-action analysis of the diver tests indicated that there were little, almost insignificant, thermal enhancements to the divers' thermal regime. This effect was attributed to the "looseness" and general bulky nature of the prototype undergarments. For the thermal storage effects of the MicroPCM® to be optimized, the

MicroPCM® layer must be configured to fit as close to the surface of the skin as possible. Due to the less-than-perfect fit of the suits, this effect was not as apparent as evidenced in the thermal manikin tests. Thus, a new, unpredicted variable surfaced – prototype garment form, fit, and function.

As FY96 came to a close, the importance of form/fit/function became apparent in new garment design and construction. A project decision was made to insert a new effort, GEN Ia, into the Approach format to improve the iterative process of fabricating the prototype Thinsulate®/MicroPCM® foam undergarments. Initiated in 1Q FY97, this aggressive effort focused on three goals. The first, to improve the physical and mechanical characteristics of the MicroPCM® foam in order to provide relief from the observed GEN I "bulkiness". The second, to increase the weight percent loading of the MicroPCM® into the foam to provide greater storage capabilities. The third, to improve on the form/ fit/function of prototype undergarments through better controls in the fabrication process. This effort culminated near the end of 1Q FY97 with a greatly improved MicroPCM® foam developed and fabricated with 57 weight percent loading of the MicroPCM® (up from 50% in the GEN I), which exhibited excellent physical and mechanical properties. In addition two garment prototypes (full-body style with gloves and booties) were delivered to divers at the NEDU for form/fit/function comparison to the GEN I and for follow-on performance demonstrations. Ultimately, the quality of the suit fabrication was still not as expected, and again form/fit/ function limited performance demonstrations.

During 2Q FY97, GEN Ib, a second iterative effort, was applied to more intensely focus on garment design using the improved MicroPCM® foam. Two (2) fabricators were selected to competitively develop and build a prototype undergarment for Team inspection and demonstration. With close scrutiny by the Team on design and fabrication, the resulting prototypes exhibited significant improvements over past efforts. And, during form/fit/function tests by the NEDU divers, the new garments were preferred over the baseline M600 commercial garments.

During 3Q FY97 fabrication efforts, a "wet-suit-style" undergarment concept was developed that could introduce a new "cutting-edge" concept to the diving industry. The Team introduced a final effort, GEN Ic, into the development scheme to explore the use of MicroPCM® foam as a "wet-suit-style" undergarment used as a replacement for the traditionally insulated dry-suit undergarment. The design, fabrication, and demonstration of a prototype garment began during the 1Q FY98.

Overall performance and completion of the technical objectives above became a concern for the Team during 2Q FY97. Because of the new GEN Ia/Ib iterative fabrication efforts inserted into the program, Team members expressed concerns that the overall program goals could not be achieved in a satisfactory manner. Diver and NSW Team members had been continually enthusiastic regarding the significance and value of MicroPCM®s to thermal protection and requested that the overall program be restructured beyond the original FY97 completion date. This would permit a thorough and comprehensive evaluation of MicroPCM® garment design and fabrication with a complete follow-on thermal and diver performance evaluation. A successful prototype demonstration could lead to enhanced thermal protection for the divers and potentially rapid commercialization. Thus, the NSWCDD Task Manager restructured the project so that the GEN I effort would be completed by the end of 4Q FY97, and a new GEN II effort was initiated during 4Q FY97 and completed by 3Q FY98.

RESULTS

Lessons learned from the GEN I/Ia/Ib efforts indicated that a suitable dry suit liner optimizing the thermal properties of the MicroPCM® foam could never be fully realized until a properly fabricated garment could be made. Although some thermal properties of the MicroPCM® foam were subjectively realized by divers, a poorly-tailored liner would never yield full thermal performance.

Acting on the lessons learned from GEN I/Ia efforts, NSWCDD implemented a new direction and strategy for fabrication of tailored MicroPCM® liners to more suitably correspond to the test divers' body structure. NEDU supplied NSWCDD with a measurement profile of the test divers, and the NSWCDD task manager served as a "living" mannequin for undergarment fabrication by competing dry suit manufacturers. "Building to fit", two prototype garments were delivered to NEDU in 4Q FY97 for form/fit/function tests, using an M600 Thinsulate® commercial undergarment as the reference garment. After successive 20-minute dives in the NEDU test pool at 41° F, while performing various range-of-motion movements and ergometric cycle ("stress-endurance") activity, the divers noticed: (1) a vastly improved garment design over the GEN I/Ia prototypes; (2) much less restriction to underwater movement versus the GEN I/Ia garments and even the reference garment, and (3) almost no sweating during the roughly 10-minute, stress-endurance ride on the ergometric cycle.

Using lessons learned from the GEN I/Ia/Ib efforts to improve the physical properties, feel, and texture of the enhanced MicroPCM® foam for the GEN Ic/II prototypes, nine new formulations were made in 4Q FY97. The new formulations used MicroPCM® concentrations from 45-65%, tailoring densities and physical structure of the polyurethane copolymer backbone, and improved "nitrogen-injection" techniques to enhance the "blow" of the foaming process. After physical properties testing, a single formulation was chosen for the FY98 garment design and fabrication efforts.

During fabrication of GEN Ib liners in FY97, sewing/stitching of the "raw" foam became a problem, as the foam under the pressure of the stitching "foot" gave way to "shredding". The problem was resolved with fabric bonding on one side of the foam. Additional problems were noticed with the multiple single layers (Polartec® inner, foam, Thinsulate®/Thermolite®, and an outer scrim) having to be intricately sewn. The initial bonding approach to solve the "shredding" problem lead to a new technique for multiple layer laminations and subsequently to "wet-suit-style" undergarment design and fabrication.

During 1Q FY98, NSWCDD and a leading U.S. manufacturer of wet suits began design and prototype construction efforts. Stretchable fabrics of polypropylene ("polypro")/lycra blends were selected for bonding to the MicroPCM® foam. A very thin, highly thermally conductive polypro/lycra fabric was selected to enhance excess body heat transfer to the foam, and a thick, looped-fiber, polypro/lycra blend was chosen to enhance insulation from the external dry suit temperatures of cold-water diving missions and to resist hyperbaric pressure "crushing" effects. Additional insulation was added to multilayer designs by using thin layers of neoprene and open-cell polyurethane. Numerous configurations of the multilayer laminates were fabricated during 4Q FY98 and subsequently used to fabricate prototype "wet-suit-style" undergarments for formal GEN II diver demonstration and test. Due to numerous inclement weather delays (hurricanes) during 4Q FY98, all test sequences at the NEDU facilities were delayed, restructured, and rescheduled over the 4Q FY98/1Q FY99 period. Formal GEN II diver testing of the prototype dry suit undergarments employing the "wet-suit-style"

design and fabrication is tentatively scheduled for early 2Q FY99. Formal reporting of the ensuing results, with conclusions and recommendations, will be available by the end of 2Q FY99.

IMPACT/APPLICATIONS

The thermodynamic and thermal energy storage capabilities associated with MicroPCM®s offer a significant impact to all forms of clothing, apparel, and garments for extreme temperature protection. During 1997-98, using the MicroPCM® foam formulations developed specifically for the NSW program, Frisby Technologies promoted technology transfer of its ComforTemp® foam to the consumer products industry through commercial ventures listed below:

- GENFOOT, Inc. of Montreal, Canada (commercial/military footwear)
- Cove Shoe Company, Martinsburg, PA (commercial/military footwear)
- Wells-Lamont, Niles, IL (commercial ski gloves)
- Orvis, Ft Worth, TX (fisherman's waders)
- Bell Sports, San Jose, CA (snowboard helmets)
- ThinkWare LLC, United Kingdom (polo helmets)
- Titleist/Footjoy Industries Worldwide (golf shoes)
- LaCrosse Industries Worldwide (boots)
- Tomasoni Topsail (sailing footwear)
- Mares Diving Products, Italy (diving products)
- CamelBak Industries, Weatherford, TX (camping/hiking product lines).

TRANSITIONS

Following FY98 development/fabrication and FY99 demonstration/testing of the GEN II undergarment prototypes, transition to the next level of NSW development should occur during the FY99-00 timeframe. Lessons learned to fabricate and investigate a full-feature, pre-commercialization product will be used.

RELATED PROJECTS

Maturation of the MicroPCM® technology has continuously opened new "windows" of opportunities and applications. The U.S. Air Force has ongoing R&D programs with Frisby Technologies to investigate and evaluate MicroPCM®s for extreme temperature applications. Commercial fire fighting proximity garments, now used by the Air Force and Navy, have Nomex® insulation as the primary medium for protection against extreme heat. During FY98/99, MicroPCM®s will be evaluated as a replacement for and/or complement to the Nomex®. In addition, MicroPCM® blends for aircraft external surface coatings and laminates are being investigated.

NCTRF is investigating the use of MicroPCM®s in other apparel applications. MicroPCM® foams are being investigated for advanced anti-exposure suits for personnel involved with Navy carrier deck operations and also for pilot safety and survivability. In a Small Business Innovative Research (SBIR) project for the Marine Corps, a new vest concept using macroencapsulated MicroPCM®s for use under chemical/biological protective garments is being evaluated.

U.S. Army Natick Research, Development, and Engineering Command (NRDEC), a division of Soldier Systems Command (SSC), is investigating cold weather footwear employing MicroPCM® foams. Testing at the Army's Cold Regions Test Center, Ft. Greely, AK is scheduled for 1Q-2Q FY99.